

Incorporation of UV Radiances Into the USU GAIM Models

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Award Number: N000140410143
<http://tipweb.nrl.navy.mil/Projects/Cicas/default.htm>

LONG-TERM GOALS

Our primary goal is to incorporate UV radiances from the SSULI and SSUSI instruments, which will be flown on the NPOESS satellites, into the USU GAIM models. A secondary goal is to conduct GAIM simulations in order to elucidate the physics underlying equatorial spread F and plasma bubbles.

OBJECTIVES

The primary USU data assimilation model is the Full Physics Kalman Filter (FPKF) model. It provides specifications and forecasts on a spatial grid that can be global, regional, or local. It uses a physics-based ionosphere-plasmasphere-polar wind model and a Kalman filter as a basis for assimilating a diverse set of real-time (or archived) measurements, and it is capable of assimilating in situ and remote sensing satellite data as well as ground-based data. The resulting specifications and forecasts are in the form of 3-dimensional electron density distributions from 90 km to 30,000 km. In addition, the FPKF model can provide global distributions for the self-consistent ionospheric drivers (neutral winds, electric fields, and particle precipitation patterns), and in its specification mode, it provides quantitative estimates for the accuracy of the reconstructed plasma densities. Because of the usefulness of this data assimilation model for DoD applications, we proposed to add an additional data source in the assimilation scheme and then conduct relevant scientific studies. Specifically, we proposed to accomplish the following objectives: (1) Assimilate UV radiances into our FPKF model and then conduct an extensive validation of the procedure; (2) Develop algorithms to assimilate data from a UV imager in a geostationary orbit; (3) Study the effect of the plasmasphere on slant Total Electron Content (TEC) measurements obtained from GPS ground receivers; and (4) Conduct simulations in an effort to determine the background ionospheric conditions just prior to the onset of equatorial spread F.

APPROACH

The Full Physics Kalman Filter model was developed at USU as part of a DoD Multidisciplinary University Research Initiative (MURI) program. The USU effort was called Global Assimilation of Ionospheric Measurements (GAIM), and the Full Physics data assimilation model was one of the two GAIM models developed. This model rigorously evolves the ionospheric (and plasmaspheric) electron density field and its associated errors using the full physical model. Advantages of this rigorous approach are expected to be most significant in data-sparse regions and during times of “severe weather.” Necessary approximations to make the model computationally tractable capitalize on the

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 30 SEP 2006		2. REPORT TYPE		3. DATES COVERED 00-00-2006 to 00-00-2006	
4. TITLE AND SUBTITLE Incorporation of UV Radiances Into the USU GAIM Models				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Utah State University,Center for Atmospheric and Space Sciences,Logan,UT,84322-4405				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

newest developments in oceanographic data assimilation (*Daley, 1991*). The model is based on a new physics-based model that is composed of an Ionosphere-Plasmasphere Model (IPM) that covers low and mid-latitudes and an Ionosphere-Polar Wind Model (IPWM) that covers high latitudes. These new physics-based models are state-of-the-art and include six ion species (NO^+ , O_2^+ , N_2^+ , O^+ , He^+ , H^+), ion and electron temperatures, and plasma drifts parallel and perpendicular to the geomagnetic field. These models use the International Geomagnetic Reference Field, which accurately describes the relative positions of the geographic and geomagnetic equators and the declination of the magnetic field lines. The physics-based models cover the altitude range from 90 to 30,000 km, which includes the E-region, F-region, topside ionosphere, plasmasphere, and polar wind. The different real-time data sources are assimilated via a Kalman filter technique and quality control algorithms are provided as an integral part of the full Kalman filter model (*Schunk et al., 2004; Scherliess et al., 2004*).

The other data assimilation model developed as part of GAIM is the Gauss-Markov Kalman Filter (GMKF) model. This data assimilation model is based on the Ionosphere Forecast Model (IFM; *Schunk et al., 1997*), which covers the E-region, F-region, and topside ionosphere up to 1400 km, and takes account of six ion species (NO^+ , O_2^+ , N_2^+ , O^+ , He^+ , H^+). However, the output of the model is a 3-dimensional electron density distribution at user specified times. In addition, auxiliary parameters are also provided, including $NmF2$, $hmF2$, NmE , hmE , slant and vertical TEC. In the Gauss-Markov Kalman Filter, the ionospheric densities obtained from the IFM constitute the background ionospheric density field on which perturbations are superimposed based on the available data and their errors. To reduce the computational requirements, these perturbations and the associated errors evolve over time with a statistical model (Gauss-Markov process) and not, as in the case of a Full-Physics-Based Model, rigorously with the physical model. As a result, the Gauss-Markov Kalman filter can be executed on a single CPU workstation. Like all assimilation techniques, the Gauss-Markov Kalman filter uses the errors on the observations and model in the analysis, and computes the errors in the match. The Gauss-Markov Kalman filter model is a global model that can support regional, higher definition assimilation windows within the model specification.

At the end of the MURI program, it was clear that the GAIM models could be very useful for numerous DoD applications after an additional data source was incorporated and scientific studies were conducted. Our approach is to pursue the four main objectives, listed above, in parallel. R. W. Schunk has overall responsibility for the project, and will participate in the validation effort (Objective 1) and the scientific studies (Objectives 3 and 4). J. J. Sojka and L. Zhu will also participate in the validation effort and scientific studies. L. Scherliess and D. C. Thompson will develop the algorithms needed to incorporate the line-of-sight UV radiances from the SSULI and SSUSI instruments (Objective 1) and the UV imager that will be on a geostationary satellite (Objective 2).

WORK COMPLETED

The primary goal of the project is to incorporate UV radiances from the SSULI and SSUSI instruments into the USU GAIM models. A secondary goal is to conduct science studies related to elucidating the fundamental processes that operate in the ionosphere, including the low-, mid-, and high-latitude domains. During the third year of the project, we accomplished the following:

- (1) Previously, we acquired 1356 Å emission data for the SSULI-type instrument and developed an algorithm to incorporate the data into our Gauss-Markov Kalman Filter model. We also assisted in defining the SSUSI SDR format specification to meet the GAIM requirement, and then we acquired

1356 Å UV radiances from the SSUSI instrument onboard the DMSP F16 satellite. We acquired 40 days (days 84-122, 2004) of limb radiances from Paul Straus. Subsequently, we performed a preliminary test run of the Gauss-Markov Kalman filter using the SSUSI UV radiances, and during the third year we conducted an additional series of tests.

(2) Previously, we began a comprehensive validation of the Ne densities obtained from the Ionosphere Forecast Model (IFM) at 840 km at high latitudes by comparing them to in situ DMSP satellite measurements. Typically, the IFM Ne densities at 840 km in the polar cap were lower than the measurements by about a factor of 2, indicating that either the density scale height above the F-region peak was too small (e.g., the plasma temperature was too small) or the neutral atomic oxygen density was too small. The study was completed this year and a paper was submitted for publication (*Bekerat et al.*, 2006). The main parameter responsible for the factor of two discrepancy was the downward electron heat flux at the IFM's upper boundary (1400 km), and a one-time adjustment of this parameter was needed to bring the IFM Ne into agreement with the DMSP Ne in the polar cap.

(3) We submitted a paper for publication entitled "Duration of an ionospheric data assimilation initialization of a coupled thermosphere-ionosphere model" by Jee et al. (2006), and a brief description of the results is given below.

(4) A publication that provides a comprehensive description of our Gauss-Markov data assimilation model has been accepted for publication. The paper by Scherliess et al. (2006) is entitled "The USU GAIM Gauss-Markov Kalman filter model of the ionosphere: Model description and validation" and it is briefly described below.

(5) Several GAIM papers and talks were presented at scientific meetings, including the Fall and Spring AGU Meetings, the CEDAR meeting, and Space Weather Week.

RESULTS

In the paper by Jee et al. (2006), we studied the effect that initial conditions have on forecast models. We addressed this problem for the thermosphere-ionosphere system by using the electron densities from the Global Assimilation of Ionospheric Measurements (GAIM) model to initialize the ionospheric part of the Thermosphere Ionosphere Nested Grid (TING) model. The electron densities from the GAIM-initialized TING model (G-TING) were compared with the output from the stand-alone TING model (S-TING) for geomagnetically quiet and disturbed times in the early April 2004 period in order to observe how long the effects of the initialization would last. Our study showed that the e-folding time of the initialization is about 2 ~ 3 hours for most conditions, although this result would probably be different if the initialization for the thermosphere was also included. However, this relaxation time displayed significant variations with latitude, local time, and height, and it may also depend on the initial electron density differences between G-TING and S-TING. Furthermore, positive ($G-TING > S-TING$) and negative ($G-TING < S-TING$) density differences have different time durations of the initialization effects. Our study also indicated that there is little variation of the relaxation time with the geomagnetic activity despite the impact of geomagnetic storms on the thermosphere-ionosphere system.

In the paper by Scherliess et al. (2006), we described our GMKF model. The GMKF uses a physics-based model of the ionosphere and a Gauss-Markov Kalman filter as a basis for assimilating a diverse

set of real-time (or near real-time) observations. The physics-based model is the IFM, which accounts for five ion species and covers the E-region, F-region, and the topside from 90 to 1400 km altitude. Within the GMKF, the IFM derived ionospheric densities constitute a background density field on which perturbations are superimposed based on the available data and their errors. In the current configuration, the GMKF assimilates slant TEC from a variable number of global positioning satellite (GPS) ground sites, bottom-side electron density (Ne) profiles from a variable number of ionosondes, in situ Ne from four DMSP satellites, and nighttime line-of-sight ultraviolet (UV) radiances measured by satellites. To test the GMKF for real-time operations and to validate its ionospheric density specifications, we have tested the model performance for a variety of geophysical conditions. During these model runs various combinations of data types and data quantities were assimilated. To simulate real-time operations, the model ran continuously and automatically, and produced 3-dimensional global electron density distributions in 15 minute increments. In this paper, the GMKF model and the results of our validation study with independent observations are presented.

Validation Studies: We have performed several validation studies of our Gauss Markov Kalman filter model and these are summarized here for completeness.

To better guide the assimilation of the nighttime UV limb scan radiances, Scherliess et al. (2005) compared 911 and 1356 Å nighttime radiances obtained from the USU GAIM data assimilation model with limb scan observations from the LORAAS and SSULI instruments. This comparison was performed for different geophysical conditions. For this study, the GAIM model assimilated slant TEC from a variable number of ground GPS sites, bottomside Ne profiles from a variable number of ionosondes, and in situ Ne from DMSP satellites and provided the 3-D global plasma density distribution in 15-min increments. The ionospheric plasma densities obtained from our GAIM model were then used to calculate associated UV radiances, which were directly compared with the observations. It was found that the 1356 Å LORASS and the 911 Å SSULI radiances agree well with the USU GAIM model results. However, the 1356 Å radiances obtained from the SSULI instrument were found to be different by a factor of 2-3 from the corresponding GAIM values.

In order to test the ability of our GAIM model to assimilate UV radiances and to test its impact on the electron density reconstruction, we also performed model runs of our GAIM model with and without assimilating the UV radiances. Figure 1 shows an example of one of these model runs. On the left side, the relative difference of the GAIM radiances and the LORASS 1356 Å radiances are shown versus tangent altitude when the UV data were not assimilated into GAIM. The right side of Figure 1 shows the same comparison, but this time after assimilating the UV radiances. The assimilation of the data slightly narrowed the distribution function and led to a more Gaussian distribution.

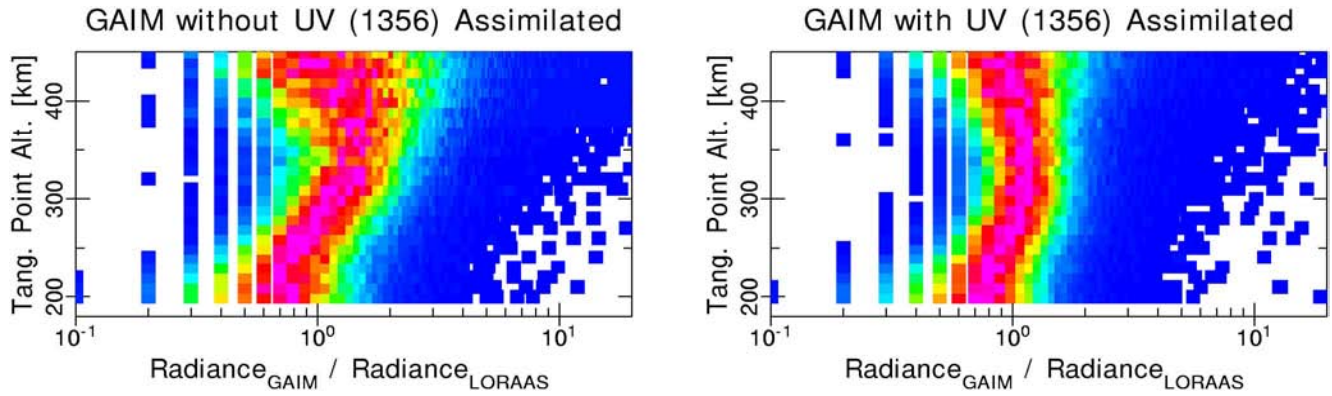


Figure 1. Relative difference between the GAIM obtained radiances and the observed LORASS 1356 Å radiances versus tangent altitude. The left side shows the case without assimilating the data and the right side shows the results after assimilation of the UV radiances.

- (1) Scherliess et al. (2006) validated the GMKF model for three month-long periods in December 2001, January 2004, and March-April 2004. These validation periods covered different solar cycle, geomagnetic activity, and seasonal conditions. In addition, different amounts and different data types were assimilated. The results were compared to independent data sets. These independent data sets included NmF2 obtained from a dynasonde located at Bear Lake Observatory near Logan, Utah, and vertical TEC observed by the TOPEX/Poseidon satellite over the oceans.
- (2) Thomson et al. (2006) used the GMKF model to study the effect of slant TEC and electron density profile data on the model fidelity. In this study, the GMKF model was run for several cases with varying combinations of slant TEC and EDP data during a 30-day study period. It was found that the assimilation of slant TEC from as many as 355 globally distributed GPS ground stations significantly improved the comparison with independent data. Furthermore, the assimilation of only ionosonde data into GAIM improved the TEC comparisons over the globe, but introduced a bias in model NmF2 owing to the specifics of the EDP handling in this version of the GMKF.
- (3) Sojka et al. (2006) compared NmF2 values obtained from the GMKF with ionosonde observations over Australia during a 3-month long period.

Collection of UV Observations from LORASS, SSULI, and SSUSI: We have worked with Pat Dandenault at NRL and Paul Strauss at AeroSpace Corporation on the collection of LORASS, SSULI, and SSUSI observations. We have received month-long SSUSI UV radiances from Paul Strauss. This data is, however, not yet in the final operational data format, which is still under consideration. We have received week-long LORASS and SSULI 1356 radiances from Pat Dandenault, which were used in the above mentioned study by Scherliess et al. (2006).

Collaborations about SSUSI and SSULI data format: We have worked with Pat Dandenault at NRL, Paul Strauss at Aerospace Corporation, and Larry Paxton at APL on the definition of the UV data formats for the SSULI and SSUSI instruments.

IMPACT/APPLICATIONS

The USU Gauss-Markov and Full Physics Kalman Filter models provide ionospheric specifications and forecasts on both global and regional grids. These specifications and forecasts are useful for DoD and civilian systems and operations, including HF communications and geo-locations, over-the-horizon (OTH) radars, surveillance, and navigation systems that use GPS signals.

TRANSITIONS

Operational Version 2.2 of the Gauss-Markov model was delivered to the Naval Research Laboratory (NRL) and the Air Force Weather Agency (AFWA) on January 15, 2005, and Operational Version 2.3 was delivered to NRL, AFWA, and the Community Coordinated Modeling Center (CCMC) on July 15, 2005. The USU Full Physics Kalman Filter model is scheduled for delivery in 2007 and it will eventually be operational at both AFWA and NOAA. Prior to this, the model will be used at NRL and CCMC so that the output will be available to the scientific community.

RELATED PROJECTS

This project resulted from a basic research MURI program called Global Assimilation of Ionospheric Measurements (GAIM). Research grade versions of our Gauss-Markov and Full Physics Kalman Filter models were developed under the MURI program, and this project provided funds to incorporate UV radiances into the GAIM models and to conduct scientific studies.

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